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DESIGN AND CALIBRATION OF A LARGE ASPECT ANGLE TOTAL HEAD PRESSURE GAGE

C. H. Hoover

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

October 1972

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by

C. H. Hoover

October 1972

BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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Details of illustrations in this document may be better studied on microfiche.

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Terminal Ballistics Laboratory

RDT&E Project No. 1T061102A33E

ABERDEEN PROVING GROUND, MARYLAND

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I. INTRODUCTION

The Height of Burst research program required the measurement of several blast parameters, one of which was the measurement of total head pressure over a large aspect angle to determine the dynamic pressure at elevations as high as 40 ft. The large aspect angle was required since in many cases the incident pressure wave and the reflected pressure wave would strike the gage from widely different angles. This problem called for designing a gage that would measure total head pressure over an aspect angle of at least $\pm$ 30° with an error of 5% or less for Mach numbers of up to 4.0.

This report presents information on the experimental work carried out in the Ballistic Research Laboratories (BRL) 24" Shock Tube on the design of the head and on the general design of the field gage. Modifications of the field gage were made for installation in the BRL Supersonic Wind Tunnel (SSWT) and Edgewood Arsenals (EA) Transonic Wind Tunnel (TSWT) to allow dynamic calibrations to be made at various Mach numbers and angles of attack. Results of these calibrations of this gage are given in both tabular and graphic form so that appropriate correction factors may be selected and applied to field data.

II. GAGE DESIGN

A preliminary investigation which included a search of available literature disclosed little in the way of total head gages suitable for a blast study program. A NACA pitot-tube design which gave accurate readings over large aspect angles was studied. This probe however was designed as a static device for use with air-speed indicators and had a long fill time and consequently a very low frequency response that would make it unsatisfactory for shock wave instrumentation. Some earlier BRL dynamic total head probes with a 30° included interior angle seemed to perform satisfactorily at 0° and small aspect angles and it was decided to pursue this design.

With consideration for the ease of instrumenting and availability of the BRL Shock Tube for testing, the first experimental probes were made to fit this facility. A 1/2" diameter piezo-electric pressure transducer with a high (250 KHz) natural frequency was used so as to clearly present the true performance of the probe. A probe mount that was capable of being oriented at angles of from 0° to 45° was designed and constructed to fit the circular top plate in the square sections of the tube. Figure 1 shows this mount with one of the experimental gages in place.

The initial probe built for the shock tube was 1" in diameter with a 30° interior cone that was 1.40" deep leaving a 1/4" diameter opening at the active surface of the piezo-gage. Figure 2 shows this gage. A series of shots was fired on this probe at a 10 PSi overpressure level. This probe appeared to work well at angles of attack up to 30°, but it was evident this design was not satisfactory from a standpoint of frequency response, having a natural frequency of only approximately 3300 Hz. Figure 3 shows a typical record from this probe.

A new probe was constructed that had an outside diameter of only 9/16" and had the 30° interior cone to a depth of 0.584" terminating in a 1/4" diameter opening at the gage surface. This probe is the one shown mounted on the shock tube revolvable mount in Figure 1. Shock tube tests of this probe showed considerable improvement. Good results were obtained at aspect angles of up to 30° and an improved frequency response of approximately 5550 Hz. Figure 4 shows a record obtained from this design.

It was desirable that a natural frequency response of approximately 10 KHz be achieved. With this criteria in mind, it was apparent that the depth of the cone would have to be decreased. Successive cuts were taken off of the cone and test shots fired until a cone depth of 15/64" with a hole diameter of 7/16" was reached. Table I shows the results of all the shock tube test shots. It should be noted that one figure of interest, the performance as a total head gage is shown only as a ratio between the side-on gage deflection and the total head gage

Figure 1-Gage Mounted in Revolvable Shock Tube Mount

Figure 2-1" Diameter Shock Tube Gage

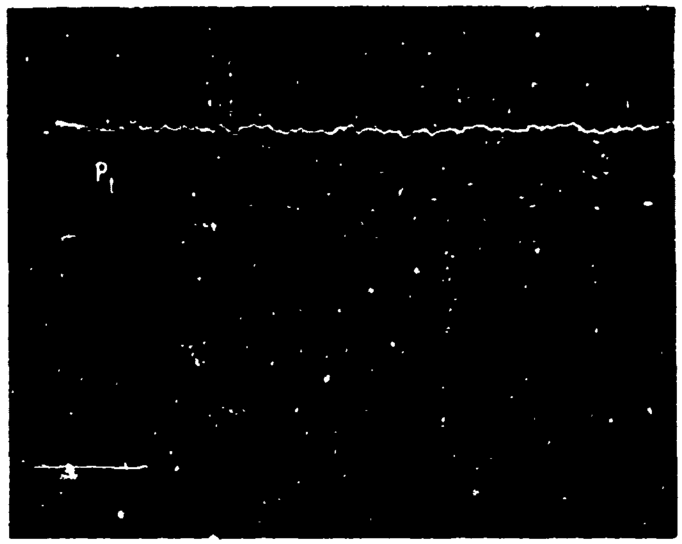


Figure 3

Typical Record From 1" Dia. Gage
$P_S = 10$ psi $P_t = 111.6\%$ $f \approx 3300$ Hz

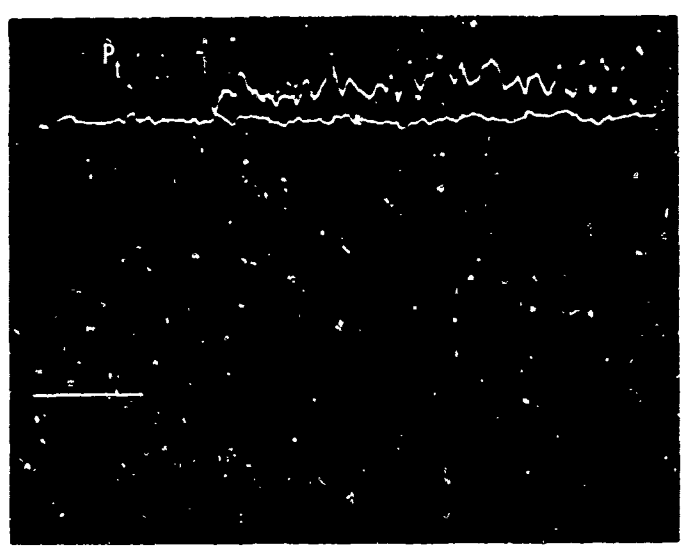
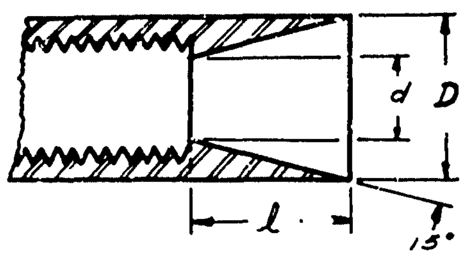


Figure 4

Typical Record From 9/16" Dia. Gage
$P_S = 10$ psi $P_t = 117.3\%$ $f \approx 5550$ Hz

Table I. Performance Data of Shock Tube Probes

D-in.	d-in.	ℓ-in.	Angle of Attack	Pressure P_s - psi	Deflection P_{s**} - in.	Deflection P_{t***} - in.	Ratio P_t/P_s - %	Cycles Counted	Time Div. *	f - Hz	Average f - Hz
1.000	.250	1.400	0°	10.62	1.380	1.540	111.6	8	4.85	3299	
1.000	.250	1.400	15°	10.60	1.380	1.535	111.2	8	4.90	3265	3299
1.000	.250	1.400	30°	10.60	1.375	1.535	111.6	9	5.40	3333	
.563	.250	.584	0°	10.50	1.360	1.605	118.0	11	3.95	5569	
.563	.250	.584	15°	10.50	1.345	1.580	117.5	11	4.00	5500	5546
.563	.250	.584	30°	10.55	1.360	1.595	117.3	11	3.95	5569	
.563	.313	.466	0°	10.67	1.400	1.630	116.4	12	3.30	7272	
.563	.313	.466	15°	10.63	1.360	1.575	115.8	8	2.30	6956	7143
.563	.313	.466	30°	10.57	1.360	1.575	115.8	9	2.50	7200	
.563	.375	.351	0°	10.54	1.365	1.595	116.8	21	4.80	8750	
.563	.375	.351	15°	10.54	1.360	1.590	116.9	14	3.20	8750	8705
.563	.375	.351	30°	10.56	1.370	1.595	116.4	14	3.25	8615	
.563	.406	.292	0°	10.42	1.345	1.615	120.1	16	3.30	9696	
.563	.406	.292	15°	10.62	1.360	1.625	119.5	17	3.45	9855	9642
.563	.406	.292	30°	10.47	1.340	1.610	120.1	15	3.20	9375	
.563	.438	.233	0°	10.48	1.370	1.600	116.8	15	2.80	10714	
.563	.438	.233	15°	10.46	1.360	1.580	116.2	14	2.60	10769	10776
.563	.438	.233	30°	10.47	1.355	1.575	116.7	16	2.95	10847	



$$\ell = \frac{D - d}{2 \tan 15°} = \frac{D - d}{.536}$$

* 1 Time Division = 0.5 msec

$$f = \frac{\text{No. of Cycles}}{\text{Units of Length}} \times .5 \text{ msec/unit}$$

**P_s - Side On

***P_t - Total Head

deflection. No attempt was made to convert this to pressure.

An attempt was made to correlate the experimental observed natural frequency data with the theory of resonating air columns. See "Sound" by Richardson, 1949 and Suffield Experimental Station Technical Paper No. 174, Jones & Muirhead, February 1960. The graph, Figure 5 and Table II, show the results of comparing the observed data with that computed from the classical formulas. The computed curve, using no end correction, shows a much higher frequency than that observed while the 0.6 D/2 correction recommended for flangeless tubes gives a curve lying below that observed.

This gage head is, of course, not a true straight sided "organ pipe", so classical theory apparently will not fit. The formula was modified from $f = \frac{c}{4(\ell + .6r)}$, where f = frequency - (Hz), c = velocity of sound - (ft/sec), ℓ = length of tube - (ft) and r = radius of tube - (ft), to $f = \frac{c}{4(\ell + .4(\frac{D + d}{4}))}$, where D = major diameter of the truncated cone and d is the minor diameter, making the factor $\frac{D + d}{4}$, the average radius of the cone. The curve computed from this modified formula more nearly fits the observed data. A value of 1278 ft/sec was assumed for c, the velocity of sound, this being a mean of the velocity at the reflected pressure and the stagnation pressure at a 10.5 psi side-on pressure. These velocity values were taken from BRL Memo Report No. 1920, The Propagation of Blast Waves Into Chambers, by Joseph F. Melichar, dated March 1968.

Time considerations dictated that no further experimentation could be carried out at that time and that field models must be designed and constructed for the summer of 1969 Height of Burst program.

Several restrictions were imposed on the design of the field gage. Number one, it must use available Schaevitz-Bytrex pressure transducers that were 1-1/8" in diameter. Two, the gage must fit in existing field mounts, and last, the construction should be as inexpensive, rugged and capable of being made as rapidly as possible.

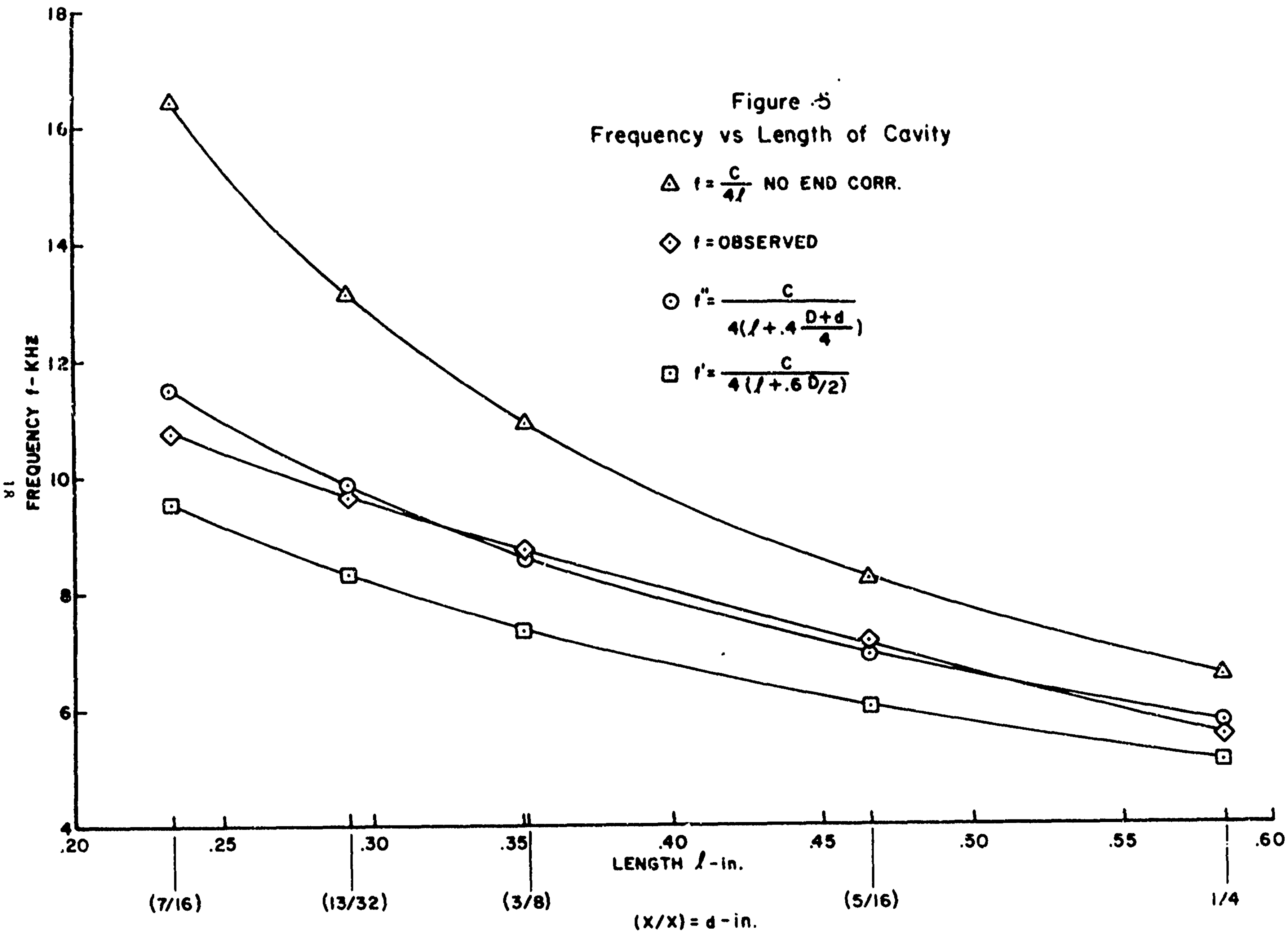


Figure 5
Frequency vs Length of Cavity

TABLE II

COMPUTED NATURAL FREQUENCY FOR 9/16" DIA. PROBE

d - in.	ℓ - in.	$\frac{D + d}{4}$	ℓ' - in.	ℓ'' - in.	f - Hz	f' - Hz	f" - Hz	Observed f - Hz
1/4	.584	.203	.753	.665	6565	5092	5765	5546
5/16	.466	.219	.635	.554	8227	6038	6921	7143
3/8	.351	.235	.520	.445	10923	7373	8616	8705
13/32	.292	.242	.461	.389	13130	8317	9856	9642
7/16	.233	.250	.402	.333	16455	9537	11514	10776

D, d & ℓ in ft.

$f = \frac{c}{4\ell}$ Frequency - Hz, No End Correction

$f' = \frac{c}{4\ell'}$ Frequency - Hz, Open End Flangeless Tube

$f'' = \frac{c}{4\ell''}$ Frequency - Hz, Empirical Fit

$\ell' = \ell + 0.6 \left(\frac{D}{2}\right)$

$\ell'' = \ell + .4 \left(\frac{D + d}{4}\right)$

c = 1278 ft/sec Av. spd. of sound-reflected and stagnation

with ℓ in inches, $f = \frac{c}{4\ell} = \frac{3834}{\ell}$ Hz

To meet these design aims the field gage was constructed in two parts, a type 303 stainless steel nose for abrasion and corrosion resistance, and an inexpensive mild steel main body. In lieu of costly machined threads on each piece for assembly the heat-shrink process was used to join the two parts together. This method proved to be both inexpensive and mechanically satisfactory. The general appearance of this gage can be seen in the photograph in Figure 6.

In addition to the field units, adaptations of the field design had to be constructed to fit mounting stings in both the BRL SSWT and the EA TSWT for dynamic calibration of the gage. These mounts will be shown in later sections.

III. CALIBRATION

The calibration of the gage was divided into three parts, one, static, in the laboratory, two, in the Supersonic Wind Tunnel for the range of Mach No. of 1.75 to 4.00 and three, in the transonic region of Mach No. of 0.5 to 1.2 in Edgewood Arsenals TSWT.

A. Static Calibrations

Two sets of static calibration curves were used in the dynamic calibration runs. The first set used in the SSWT tests had a zero output point at 14.797 psia with a positive slope (14.797 psia to 42.00 psia) of 0.1819 psi/millivolt and a negative slope (14.797 psia to 2 psia) of 0.1879 psi/millivolt. The second set of calibration points were made with the same pressure transducer but with a different and carefully matched signal conditioner and power supply. This group of instruments was used for all the TSWT test runs. On this set, zero output was adjusted to occur at 15.00 psia. The linearity was again excellent both positive and negative with just a slightly different slope in the two modes. The positive calibration gave a linear slope of 0.1798 psi/millivolt between 15.00 and 50.00 psia while the negative gave 0.1849 psi/millivolt between 15.00 and approximately 1 psia. The plotted curve for the second set of calibration points is shown in Figure 7.

Figure 6 -Completed Field Gage

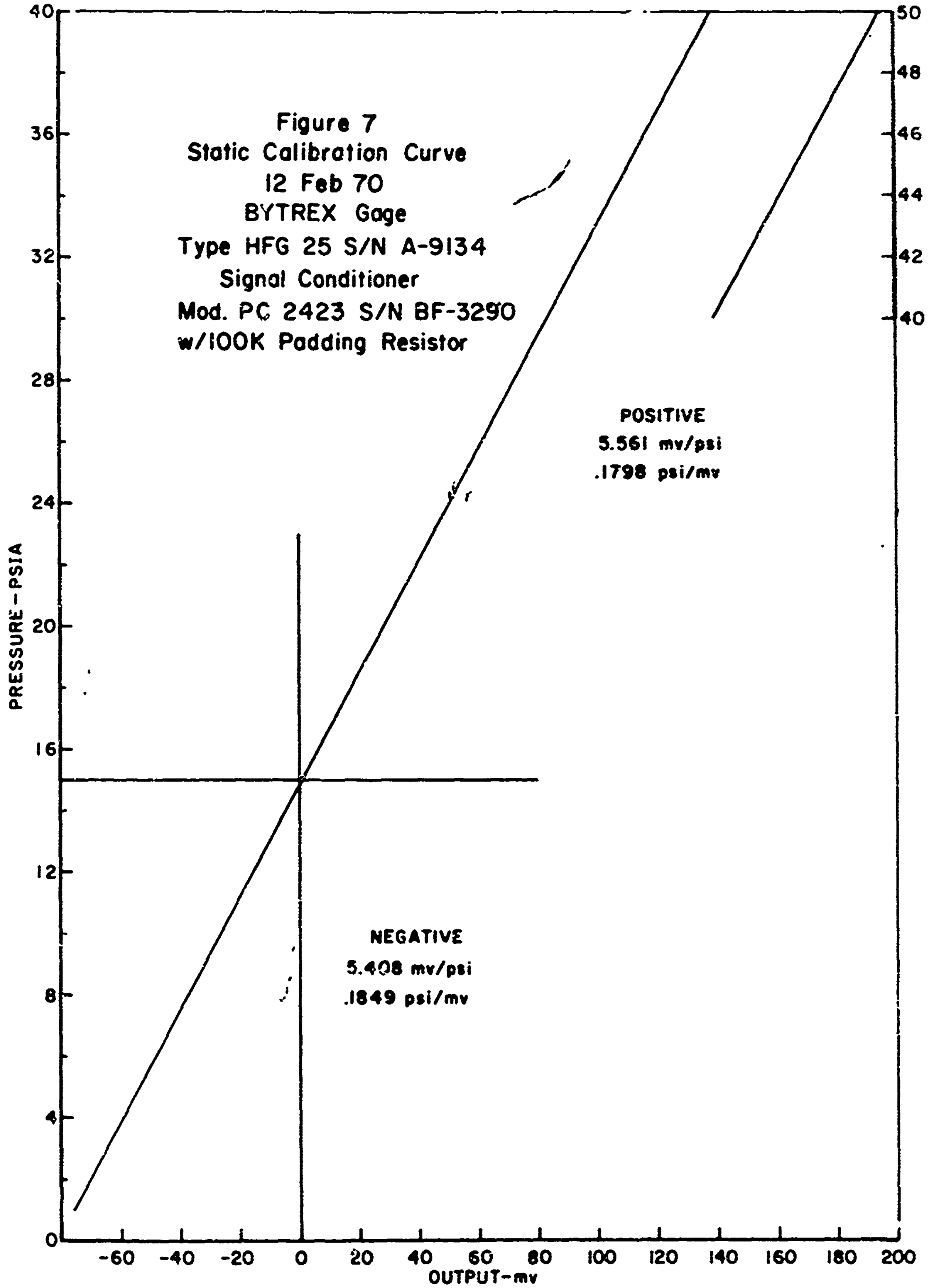


Figure 7
Static Calibration Curve
12 Feb 70
BYTREX Gage
Type HFG 25 S/N A-9134
Signal Conditioner
Mod. PC 2423 S/N BF-3290
w/100K Padding Resistor
POSITIVE
5.561 mv/psi
.1798 psi/mv
NEGATIVE
5.408 mv/psi
.1849 psi/mv
PRESSURE – PSIA
OUTPUT–mv
0
4
8
12
16
20
24
28
32
36
40
42
44
46
48
50
-60
-40
-20
60
80
100
120
140
160
180
200

B. Supersonic Wind Tunnel Tests

Dynamic calibrations under supersonic flow conditions were carried out in the EBL - BRL - SSWT under the direction of Mr. M. A. Sylvester. Appropriate adapters were constructed to attach the total head probe nose section to the strut of the remote controlled roll head. Figure 8 shows this section mounted on the head in the tunnel. Use of this head permitted a continuously variable angle of attack of from 0° to 40°.

These test runs were made under steady flow conditions which permitted the gage electrical output to be visually read from the digital voltmeter. It was evident that the pressure transducer was sensitive to temperature changes during a run. This was most noticeable during the initial run of a series when the cooling of the gage was most pronounced. This would be indicated by a relatively large difference in gage output between the initial $\alpha = 0°$ and the end $\alpha = 0°$. In these cases the data was corrected assuming a linear temperature change effect. In all cases the output was corrected for the gage static zero output as noted in the tables.

From the corrected output, the total head pressure was computed using the static calibration data. The error in percent was derived from the difference in pressure between total head pressure at $\alpha = 0°$ and at $\alpha = n°$ divided by the pressure at $\alpha = 0°$. This data in both tabular and graphic form is presented in Appendix A.

In addition to the pressure data obtained from these tests, Schlieren photographs at each Mach number and aspect angle were taken showing the flow pattern around the gage. A sample of these photos taken at Mach 4 and aspect angles of 0° and 30° is shown in Figure 9.

One other bit of data of interest is the comparison of the observed total head pressure at 0° aspect angle with that calculated from the stagnation pressure as per NACA document No. 1135, Equations, Tables and Charts for Compressible Flow. Table III shows this comparison.

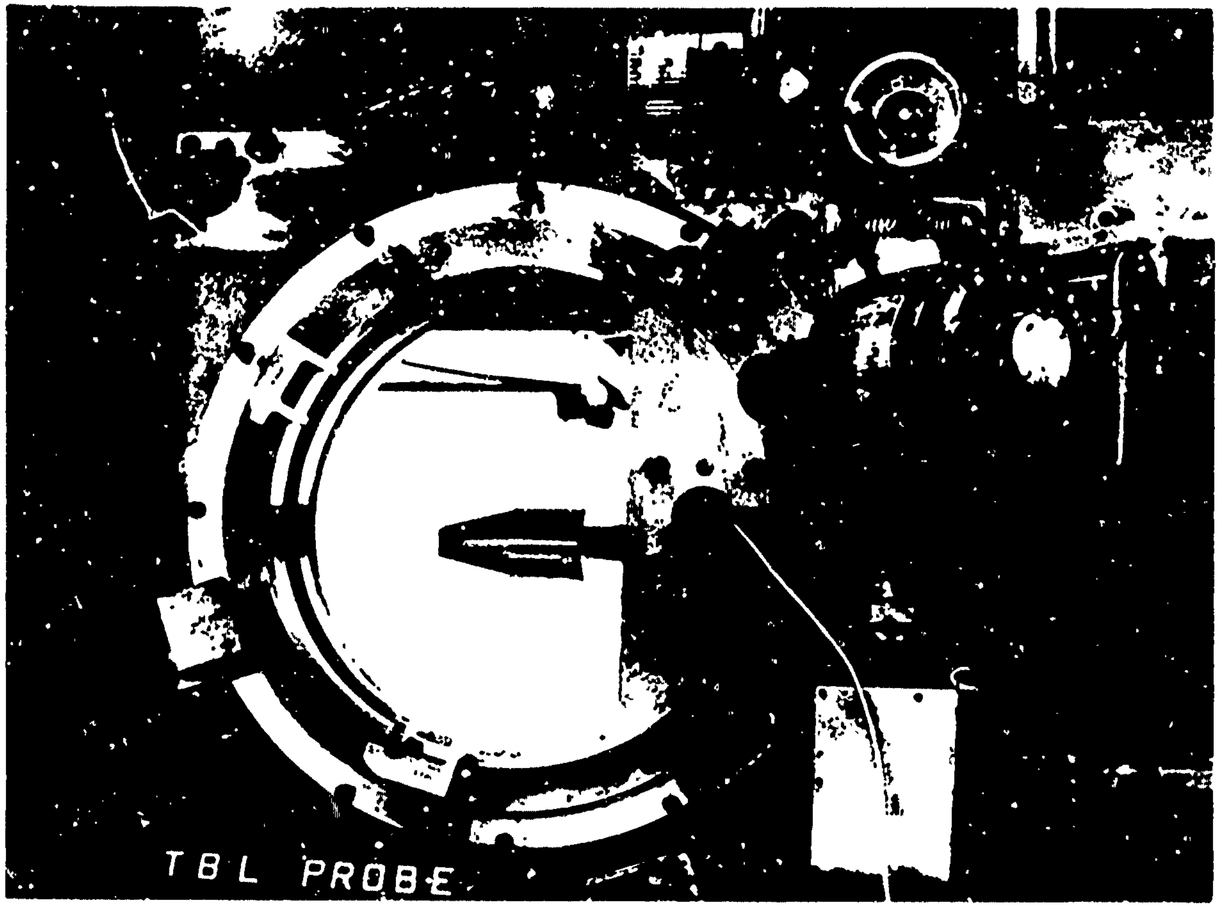
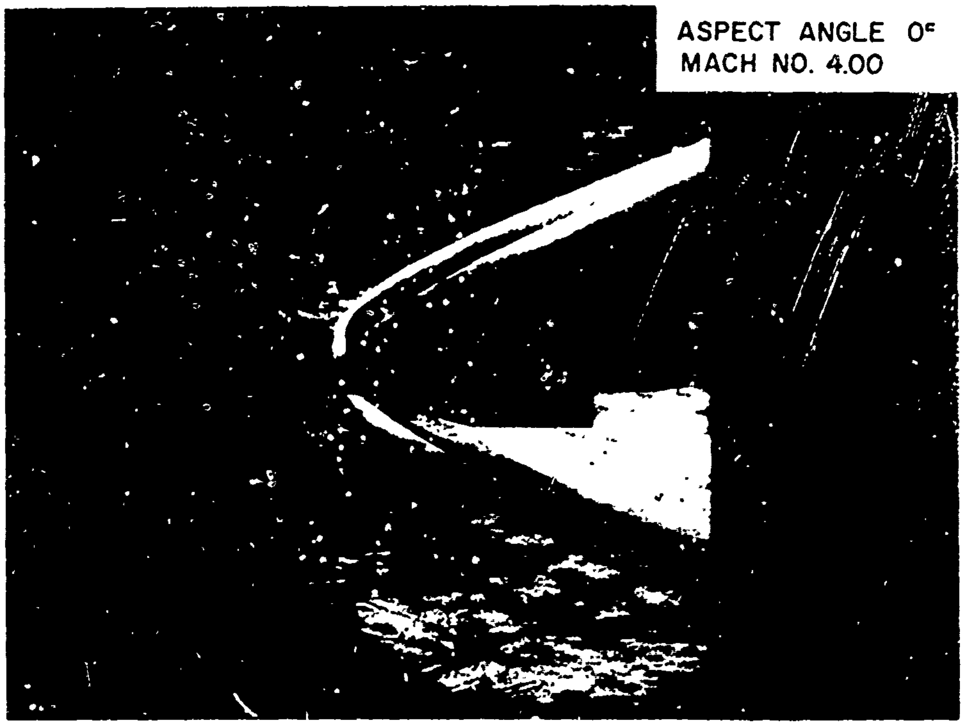


Figure 8 - SSWT Total Head Installation



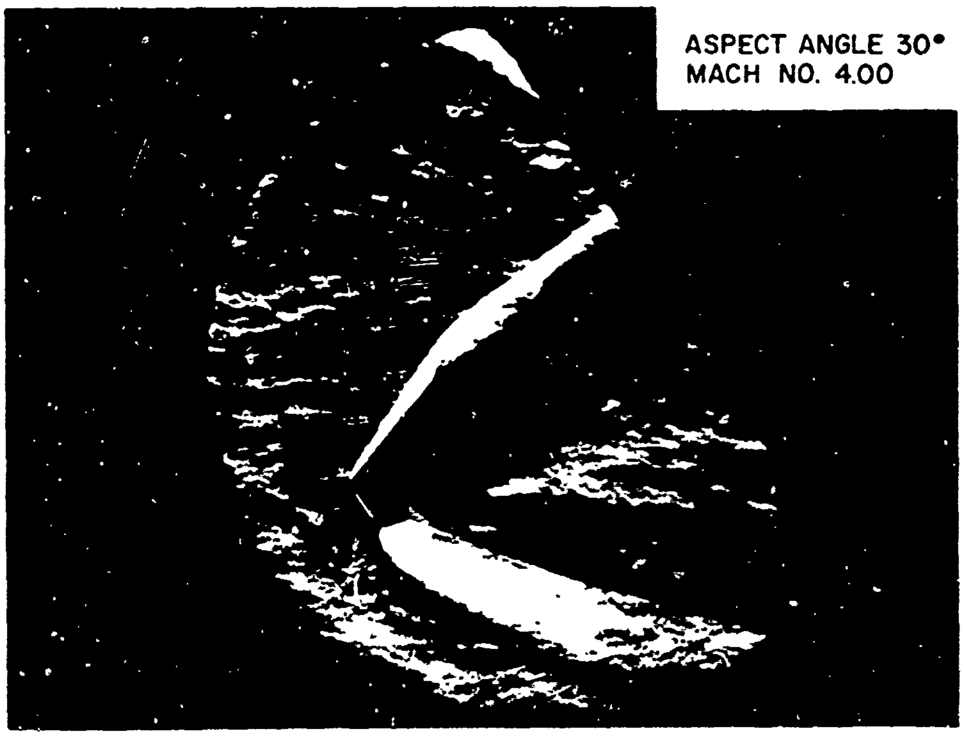


Figure 9. Schlieren Photos of SSWT Runs.

Table III. Comparison of Calculated and Observed Total Head Pressure

Mach No.	Reynolds No. 10^6/in.	P_t - Calc. psia	P_t - Obs. psia	ΔP_t psi	ΔP_t %
1.75	0.18	6.426	6.392	0.034	0.53
1.75	0.45	16.221	16.198	0.023	0.14
1.75	0.62	22.484	22.413	0.071	0.32
2.00	0.18	6.104	6.061	0.043	0.70
2.00	0.45	15.398	15.198	0.200	1.30
2.50	0.18	5.377	5.325	0.052	0.97
2.50	0.45	13.635	13.493	0.142	1.04
3.00	0.18	4.549	4.500	0.049	1.08
3.00	0.45	11.561	11.388	0.173	1.50
3.50	0.18	3.769	3.739	0.030	0.80
3.50	0.45	9.546	9.403	0.143	1.50
4.00	0.18	3.125	3.085	0.040	1.28
4.00	0.45	7.879	7.703	0.176	2.24
4.00	0.62	10.924	10.817	0.107	0.98

Average ΔP_t = 1.03% Low

Aspect Ratio = 0°

C. Transonic Wind Tunnel Tests

Dynamic calibrations in the transonic range were carried out at Edgewood Arsenals Transonic Wind Tunnel under the direction of Mr. Abe Flatau and Mr. Donald Olson. This data is presented in Appendix, B.

IV. DISCUSSION

The final product of all the test data taken is a series of curves of gage error versus Mach number for various aspect angles from 10° to 40°. These curves are shown in Figure 10. From this group of curves, knowing the approximate Mach number and angle of incidence of the shock wave, a correction factor may be selected to be applied to field data of total head pressure to make it more nearly correct.

It is realized that this correction factor is not exact because the wind tunnel data was taken at a different Reynolds number than would be experienced under the higher (up to 200 psi) over pressures of field conditions. In all cases data from the run with the highest Reynolds number was used in the final graph as this data more nearly approached field conditions. The supersonic wind tunnel data was taken at Reynolds numbers of from 0.18 to 0.62 x 10^6/in. Transonic wind tunnel runs were made at Reynolds numbers of from 0.30 x 10^6/in. to 0.40 x 10^6/in. Field data however was taken at Reynolds numbers of from 0.43 to 2.00 x 10^6/in. depending on the overpressure level. This calibration data is probably the nearest approach to data taken under field conditions that is possible with existing wind tunnel and shock tubes.

The data obtained indicates that as the Reynolds number increases, the error factor decreases but grows greater as the Mach number increases. Up to an aspect angle of approximately 30° the error factor is less than the desired maximum of 5% except for a small region about Mach 0.7 and Mach 1.0 .

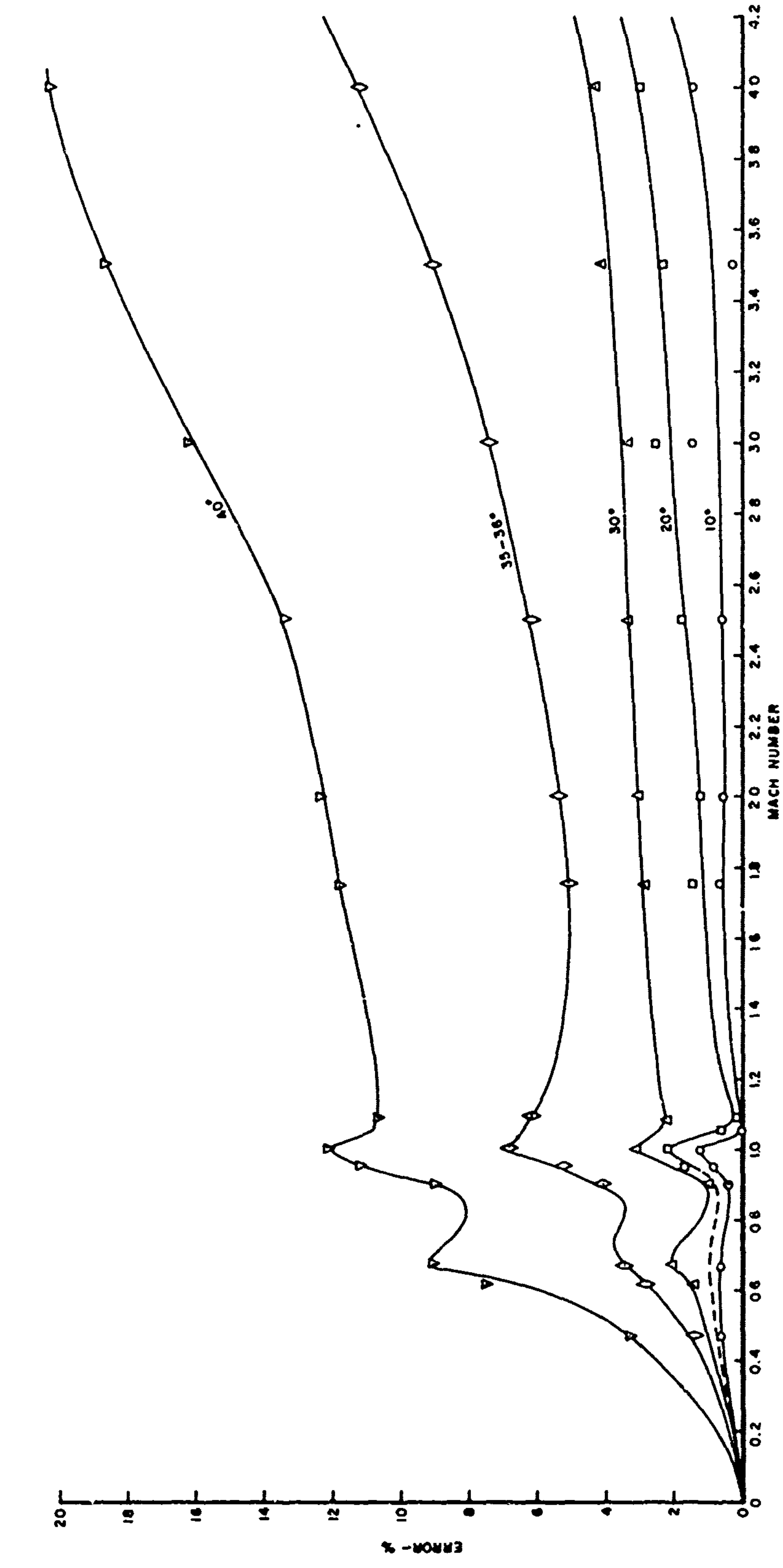


Figure 10– Error vs Mach Number for Various Angles of Attack

V. CONCLUSION

The conclusion may be drawn that the general design of this total head pressure probe may be used where the angle of incidence will be 30° or less with an error of less than 5%. At angles greater than this appropriate correction factors may be applied to the field data.

ACKNOWLEDGMENT

The author wishes to express his appreciation for the helpful comments and suggestions of Messrs. George Coulter, John Keefer and Ralph Reisler of these laboratories in the preparation of this report, and to Mr. M. A. Sylvester of the BRL SSWT and Mr. Donald Olson of EA TSWT for the compilation of data from their facilities.

APPENDIX A

TABLES AND GRAPHS FROM SSWT TEST RUNS

EXPLANATION OF TABULAR DATA IN APPENDIX A

Appendix A presents the data from the calibration test runs made in the BRL SSWT in both tabular and graphic form for each combination of Mach and Reynolds numbers used.

The following explanation of the tables holds true for all runs:

(1) Column one, aspect angle (α) in degrees was read from the remote angle indicator of the wind tunnel roll head.

(2) The second column, observed gage output in millivolts, was visually read from a sensitive digital voltmeter after a reasonably steady state existed.

(3) Column three, corrected gage output in millivolts is obtained by adding or subtracting a static gage zero reading from the observed output. In the cases where the particular run was the first of a series after starting up the wind tunnel, it was necessary to use a different static gage zero reading at the beginning of the run and at the end to compensate for an apparent temperature effect in the gage. The values for these runs would be corrected proportionally from beginning to end. After the first run of a series, it was assumed the sensor had stabilized itself and the records were corrected for only one gage zero reading throughout.

(4) Column four, the total head pressure in psig was taken from the calibration curve or was computed from the slope of the curve.

(5) The fifth column, total head pressure in terms of absolute pressure, is the gage pressure of column four added to or subtracted from the observed atmospheric pressure (Patm) at the time of the run.

(6) Column six, error in psi, is obtained by subtracting the total head pressure at $\alpha = N°$ from the pressure at $\alpha = 0°$

(7) The last column merely converts this reading in psi to percentile, $\Delta P/P_{t\alpha = 0}$ = % Error.

TABLE A-I

SSWT Test M = 1.75 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-45.97	-45.66	-8.580	6.392		
5	-46.13	-45.80	-8.606	6.366	0.026	0.46
10	-46.28	-45.93	-8.630	6.342	0.050	0.78
15	-46.43	-46.06	-8.655	6.317	0.075	1.17
20	-46.55	-46.15	-8.672	6.300	0.092	1.44
25	-46.80	-46.38	-8.715	6.257	0.135	2.11
30	-47.30	-46.86	-8.805	6.167	0.225	3.52
35	-48.07	-47.61	-8.946	6.026	0.366	5.73
30	-47.37	-46.89	-8.811	6.161	0.231	3.61
20	-46.71	-46.20	-8.681	6.291	0.101	1.58
10	-46.43	-45.90	-8.625	6.347	0.045	0.70
0	-46.13	-45.58	-8.564	6.408	-0.016	-0.25

Patm = 14.972 psia

Static Gage Zero -0.31 mv beginning
-0.55 mv end

TABLE A-II

SSWT Test M = 1.75 Re = 0.45 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	+6.88	+6.74	+1.224	16.198		
5	+6.47	+6.33	+1.150	16.124	0.074	0.46
10	+6.20	+6.06	+1.100	16.074	0.124	0.77
15	+5.80	+5.66	+1.028	16.002	0.196	1.21
20	+5.47	+5.33	+0.968	15.942	0.256	1.58
25	+4.86	+4.72	+0.857	15.831	0.367	2.27
30	+3.99	+3.85	+0.699	15.673	0.525	3.24
35	+2.12	+1.98	+0.359	15.333	0.865	5.34
40	-3.70	-3.84	-0.721	14.253	1.945	12.01
37.5	-0.45	-0.59	-0.111	14.863	1.335	8.24
32.5	+3.72	+3.58	+0.650	15.624	0.574	3.54
30	+4.16	+4.02	+0.730	15.704	0.494	3.05
27.5	+4.60	+4.46	+0.810	15.784	0.414	2.56
22.5	+5.20	+5.06	+0.919	15.893	0.305	1.88
20	+5.43	+5.29	+0.961	15.935	0.263	1.62
17.5	+5.57	+5.43	+0.986	15.960	0.238	1.47
10	+5.97	+5.83	+1.059	16.033	0.165	1.02
0	+6.70	+6.56	+1.191	16.165	0.033	0.2

Patm = 14.974 psia

Static Gage Zero +0.14 mv

TABLE A-III

SSWT Test M = 1.75 Re = 0.62×10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	+41.10	+40.96	+7.438	22.413		
5	+40.63	+40.49	+7.353	22.328	0.085	0.38
10	+40.26	+40.12	+7.286	22.261	0.152	0.68
15	+39.79	+39.65	+7.200	22.175	0.238	1.06
20	+39.32	+39.18	+7.115	22.090	0.323	1.44
25	+38.55	+38.41	+6.975	21.950	0.463	2.07
30	+37.54	+37.40	+6.792	21.767	0.646	2.88
35	+34.90	+34.76	+6.312	21.287	1.126	5.02
40	+26.63	+26.49	+4.811	19.786	2.627	11.72
37.5	+30.96	+30.82	+5.597	20.572	1.841	8.21
32.5	+36.90	+36.76	+6.676	21.650	0.763	3.40
30	+37.65	+37.51	+6.812	21.787	0.626	2.79
27.5	+38.28	+38.14	+6.926	21.901	0.512	2.28
23.7	+38.96	+38.82	+7.050	22.025	0.388	1.73
22.5	+39.10	+38.96	+7.075	22.050	0.363	1.62
20	+39.36	+39.22	+7.122	22.097	0.316	1.41
10	+40.13	+39.99	+7.262	22.237	0.176	0.79
0	+41.10	+40.96	+7.438	22.413	0.000	0.00

Patm = 14.975 psia

Static Gage Zero + 0.14 mv

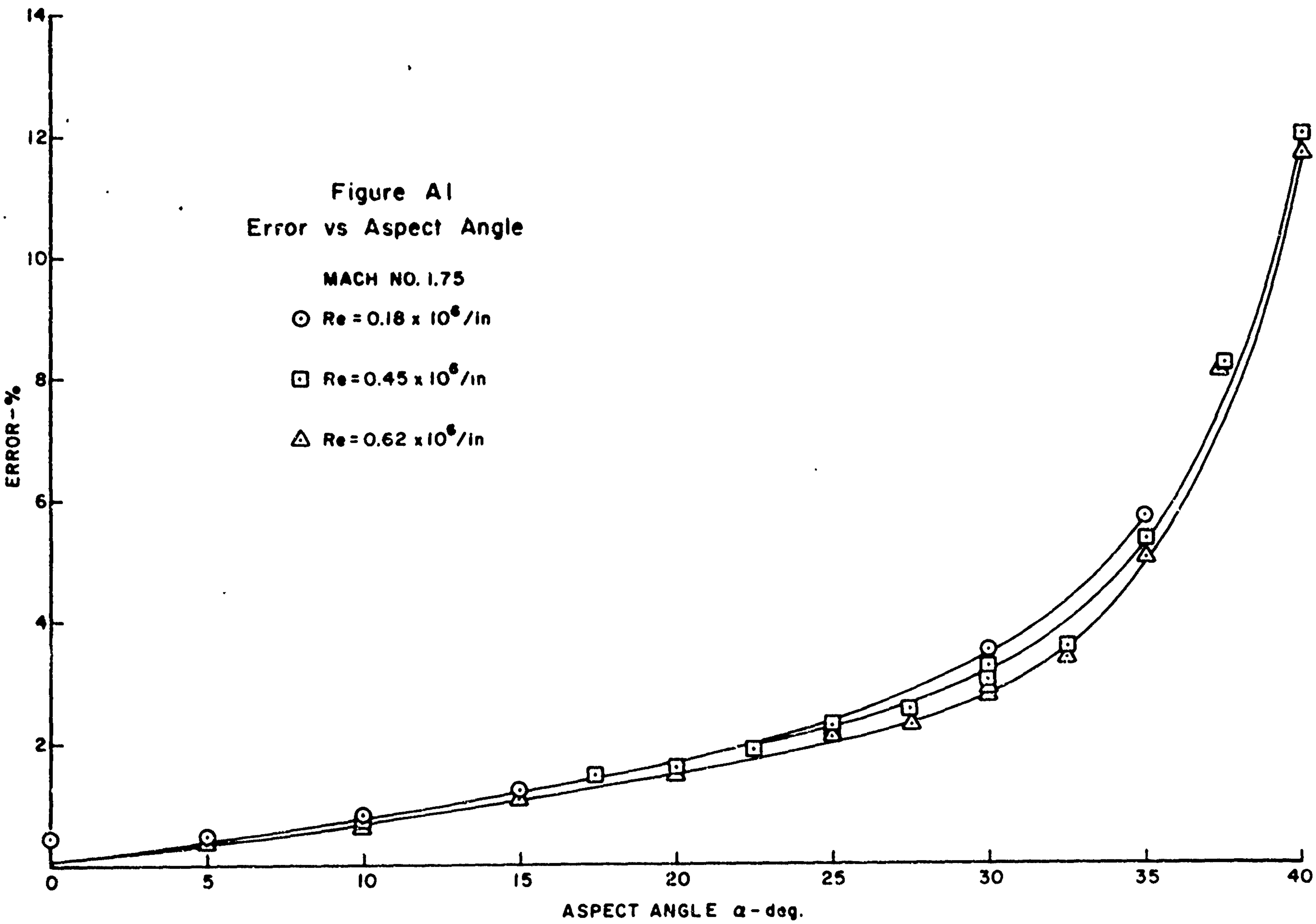


Figure A1
Error vs Aspect Angle
MACH NO. 1.75
Re = 0.18 x 10^6/in
Re = 0.45 x 10^6/in
Re = 0.62 x 10^6/in
ERROR-%
ASPECT ANGLE α - deg.
0
5
10
15
20
25
30
35
40
2
4
6
8
10
12
14

TABLE A-IV

SSWT Test M = 2.00 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-47.60	-47.43	-8.907	6.061		
5	-47.82	-47.62	-8.943	6.025	.036	0.59
10	-47.98	-47.75	-8.967	6.001	.060	0.99
15	-48.07	-47.81	-8.979	5.989	.072	1.19
20	-48.30	-48.02	-9.018	5.950	.111	1.83
25	-48.60	-48.29	-9.069	5.899	.162	2.67
30	-48.93	-48.59	-9.125	5.843	.218	3.60
35	-49.79	-49.42	-9.281	5.687	.374	6.17
40	-51.95	-51.56	-9.683	5.285	.776	12.80
37.5	-50.88	-50.46	-9.476	5.492	.569	9.39
32.5	-49.36	-48.91	-9.185	5.783	.278	4.59
30	-49.25	-48.78	-9.161	5.807	.254	4.19
20	-48.61	-48.11	-9.035	5.933	.128	2.11
10	-48.31	-47.78	-8.973	5.995	.066	1.09
0	-48.10	-47.54	-8.928	6.040	.021	0.35

Patm = 14.968 psia

Static Gage Zero -0.17 mv beginning
-0.56 mv end

TABLE A-V

SSWT TEST M = 2.00 Re = 0.45 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	+1.83	+1.27	+0.231	15.198		
5	+1.60	+1.04	+0.189	15.156	0.042	0.28
10	+1.35	+0.79	+0.144	15.111	.087	0.57
15	+1.07	+0.51	+0.093	15.060	.138	0.91
20	+0.80	+0.24	+0.044	15.011	.187	1.23
25	+0.18	-0.38	-0.071	14.896	.302	1.99
30	-0.64	-1.20	-0.225	14.742	.456	3.00
35	-2.56	-3.12	-0.586	14.381	.817	5.38
40	-8.17	-8.73	-1.639	13.328	1.870	12.30
37.5	-5.07	-5.63	-1.057	13.910	1.288	8.47
32.5	-1.10	-1.66	-0.312	14.655	.543	3.57
30	-0.75	-1.31	-0.246	14.721	.477	3.14
20	+0.60	+0.04	+0.002	14.969	.229	1.51
10	+1.10	+0.54	+0.098	15.065	.133	0.88
0	+1.63	+1.07	+0.194	15.161	.037	0.24

Patm = 14.967 psia

Static Gage Zero +0.56 mv

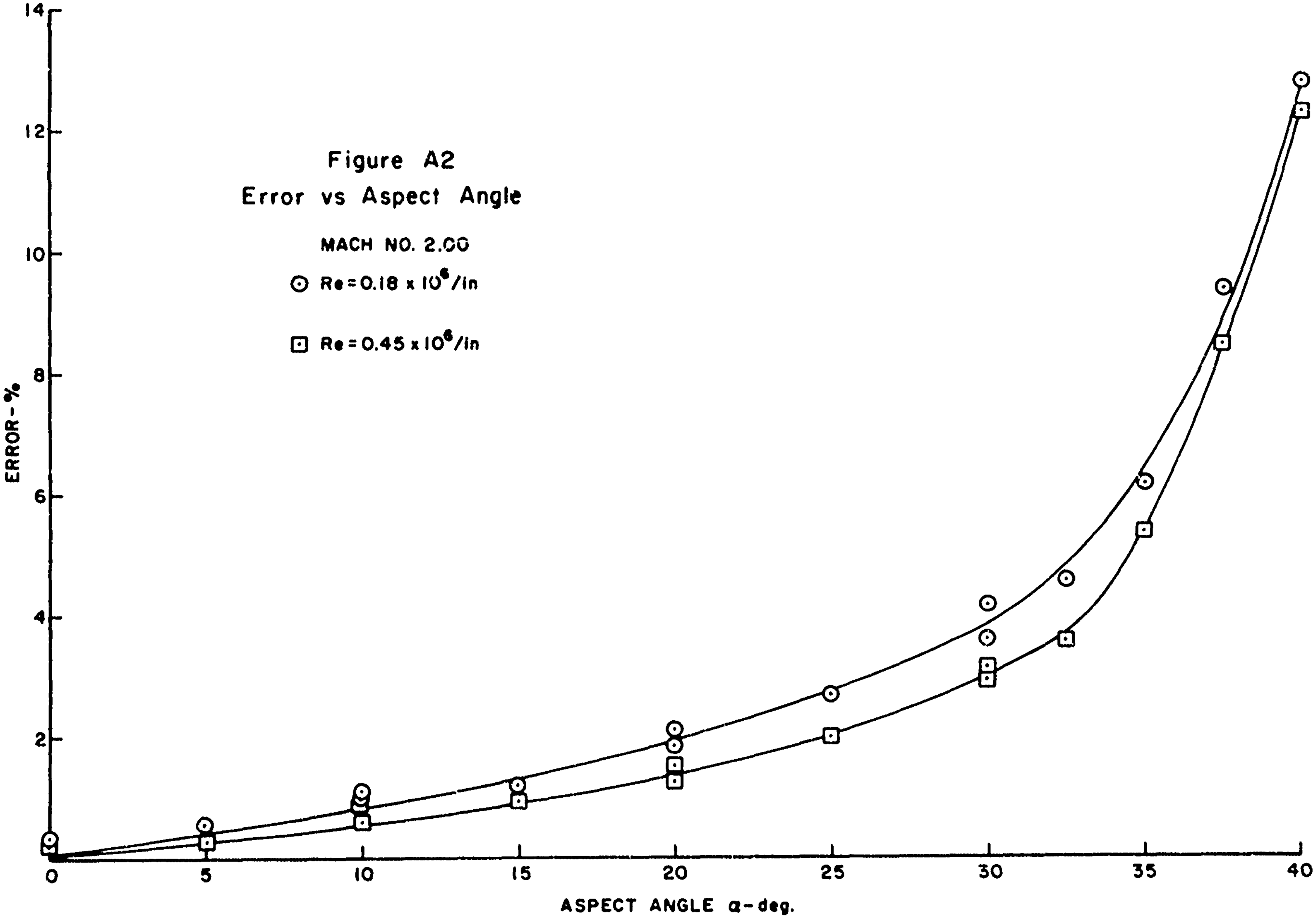


Figure A2
Error vs Aspect Angle

TABLE A-VI

SSWT Test M = 2.50 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-51.48	-51.28	-9.636	5.325		
5	-51.52	-51.30	-9.639	5.322	0.003	0.06
10	-51.88	-51.64	-9.703	5.258	0.067	1.25
15	-52.18	-51.92	-9.756	5.205	0.120	2.25
20	-52.44	-52.17	-9.803	5.158	0.167	3.14
25	-52.68	-52.39	-9.844	5.117	0.208	3.91
30	-52.95	-52.64	-9.891	5.070	0.255	4.79
35	-53.70	-53.38	-10.030	4.931	0.394	7.40
40	-55.58	-55.24	-10.380	4.581	0.744	13.97
45	-58.60	-58.24	-10.943	4.018	1.307	24.54
50	-62.46	-62.08	-11.665	3.296	2.029	38.10
47.5	-60.74	-60.35	-11.340	3.621	1.704	32.00
42.5	-57.13	-56.72	-10.658	4.303	1.022	19.19
40	-55.80	-55.37	-10.404	4.557	0.768	14.42
30	-53.34	-52.90	-9.940	5.021	0.304	5.71
20	-52.85	-52.39	-9.844	5.117	0.208	3.91
10	-52.41	-51.93	-9.758	5.203	0.122	2.29
0	-52.05	-51.56	-9.688	5.273	0.052	0.98

Patm = 14.961 psia

Static Gage Zero -0.20 mv beginning
-0.49 mv end

TABLE A-VII

SSWT Test $M = 2.50$ $Re = 0.45 \times 10^6$/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-8.29	-7.80	-1.465	13.493		
5	-8.27	-7.78	-1.461	13.497	.004	0.03
10	-8.66	-8.17	-1.534	13.415	.078	0.58
15	-9.08	-8.59	-1.613	13.345	.148	1.10
20	-9.53	-9.04	-1.698	13.260	.233	1.73
25	-10.01	-9.52	-1.788	13.170	.323	2.39
30	-10.68	-10.19	-1.914	13.044	.449	3.33
35	-12.70	-12.21	-2.293	12.665	.828	6.14
40	-17.85	-17.36	-3.260	11.698	1.795	13.30
45	-25.50	-25.01	-4.697	10.261	3.232	23.95
50	-36.01	-35.52	-6.671	8.287	5.206	38.58
47.5	-31.09	-30.60	-5.747	9.211	4.282	31.73
42.5	-21.56	-21.07	-3.967	10.991	2.502	18.54
40	-17.91	-17.42	-3.271	11.687	1.806	13.38
37.5	-15.11	-14.62	-2.746	12.212	1.281	9.49
32.5	-11.35	-10.86	-2.040	12.918	0.575	4.26
30	-10.88	-10.39	-1.951	13.007	.486	3.60
20	-9.80	-9.31	-1.748	13.210	.283	2.10
10	-8.90	-8.41	-1.579	13.379	.114	0.84
0	-8.40	-7.91	-1.485	13.473	.020	0.15

Patm = 14.958 psia

Static Gage Zero -0.49 mv

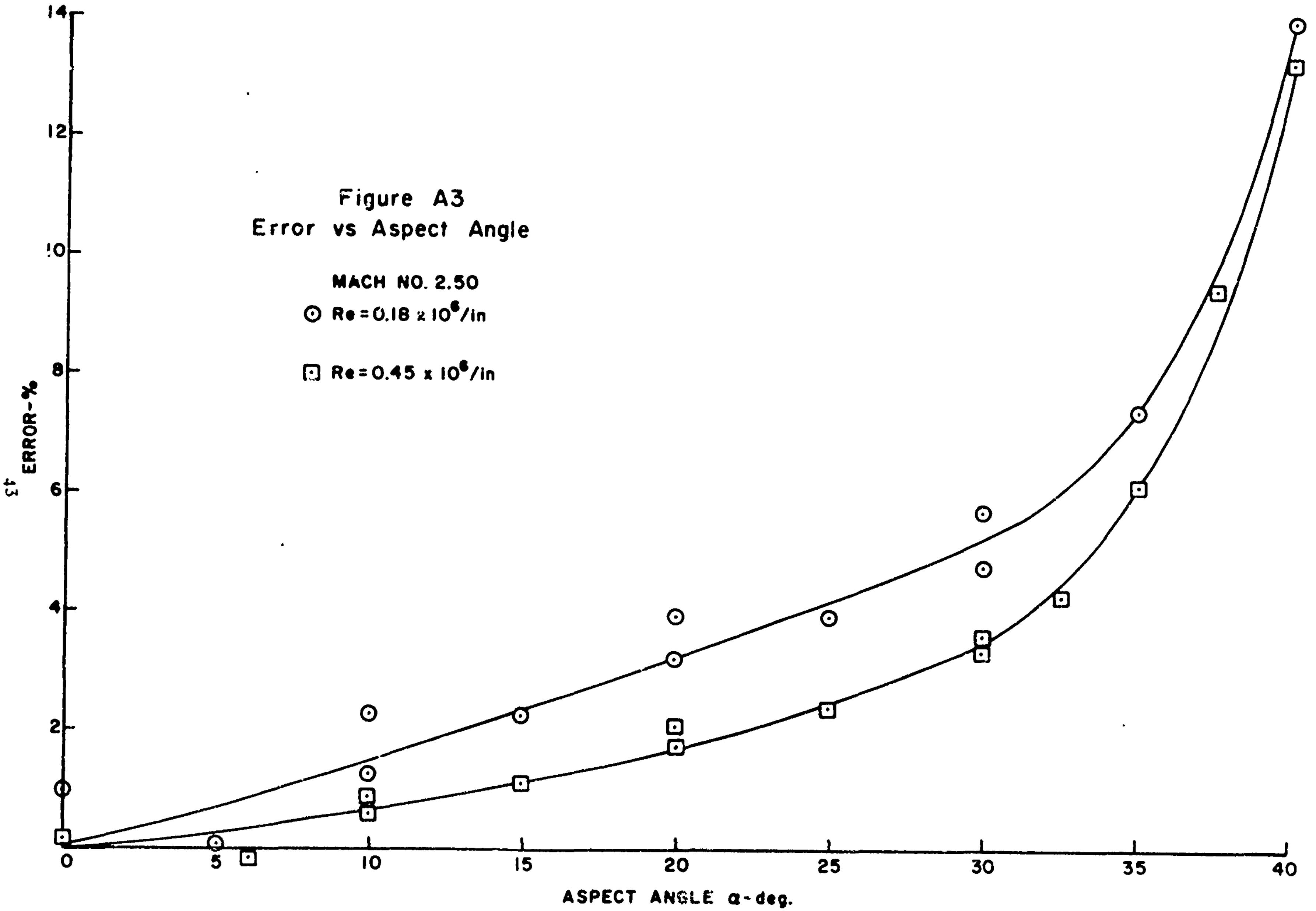


Figure A3
Error vs Aspect Angle
MACH NO. 2.50
Re = 0.18 x 10^6/in
Re = 0.45 x 10^6/in
ERROR-%
ASPECT ANGLE α-deg.
0
2
4
6
8
10
12
14
5
15
20
25
30
35
40

TABLE A-VIII

SSWT Test M = 3.00 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-56.10	-55.64	-10.453	4.500		
5	-56.36	-55.88	-10.500	4.453	0.047	1.04
10	-56.62	-56.12	-10.545	4.408	0.092	2.04
15	-56.81	-56.28	-10.575	4.378	0.122	2.71
20	-57.07	-56.52	-10.620	4.333	0.167	3.71
25	-57.29	-56.72	-10.658	4.295	0.205	4.56
30	-57.49	-56.89	-10.690	4.263	0.237	5.27
35	-58.40	-57.78	-10.857	4.096	0.404	8.98
40	-60.32	-59.67	-11.212	3.741	0.759	16.87
45	-62.84	-62.17	-11.682	3.271	1.229	27.31
50	-66.08	-65.39	-12.286	2.667	1.833	40.73
47.5	-64.04	-63.32	-11.897	3.056	1.444	32.09
42.5	-61.72	-60.98	-11.458	3.495	1.005	22.33
40	-60.75	-59.99	-11.272	3.681	0.819	18.20
37.5	-59.30	-58.51	-10.994	3.959	0.541	12.02
30	-57.94	-57.13	-10.735	4.218	0.282	6.27
20	-57.54	-56.71	-10.656	4.297	0.203	4.51
10	-57.10	-56.25	-10.570	4.383	0.127	2.82
0	-56.57	-55.70	-10.466	4.487	0.013	0.29

Patm = 14.953 psia

Static Gage Zero -0.46 mv beginning
-0.87 mv end

TABLE A-IX

SSWT Test M = 3.00 Re = 0.45×10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-19.82	-18.95	-3.561	11.388		
5	-20.23	-19.36	-3.638	11.311	0.077	0.68
10	-20.71	-19.84	-3.728	11.221	0.167	1.47
15	-20.92	-20.05	-3.767	11.182	0.206	1.81
20	-21.34	-20.47	-3.846	11.103	0.285	2.50
25	-21.67	-20.80	-3.908	11.041	0.347	3.05
30	-21.82	-20.95	-3.936	11.013	0.375	3.29
35	-24.30	-23.43	-4.402	10.547	0.841	7.38
40	-29.60	-28.73	-5.398	9.551	1.837	16.13
45	-36.70	-35.83	-6.732	8.217	3.171	27.85
50	-45.15	-44.28	-8.320	6.629	4.759	41.77
47.5	-39.50	-38.63	-7.258	7.691	3.697	32.46
42.5	-32.90	-32.03	-6.018	8.931	2.457	21.57
40	-30.01	-29.14	-5.474	9.475	1.913	16.80
37.5	-26.01	-25.14	-4.723	10.226	1.162	9.68
32.5	-22.97	-22.10	-4.152	10.797	0.591	5.19
30	-22.23	-21.36	-4.013	10.936	0.392	3.97
20	-21.60	-20.73	-3.895	11.054	0.334	2.93
10	-20.73	-19.86	-3.732	11.217	0.171	1.50
0	-19.68	-18.81	-3.534	11.405	0.017	0.15

Patm = 14.949 psia

Static Gage Zero -0.87 mv

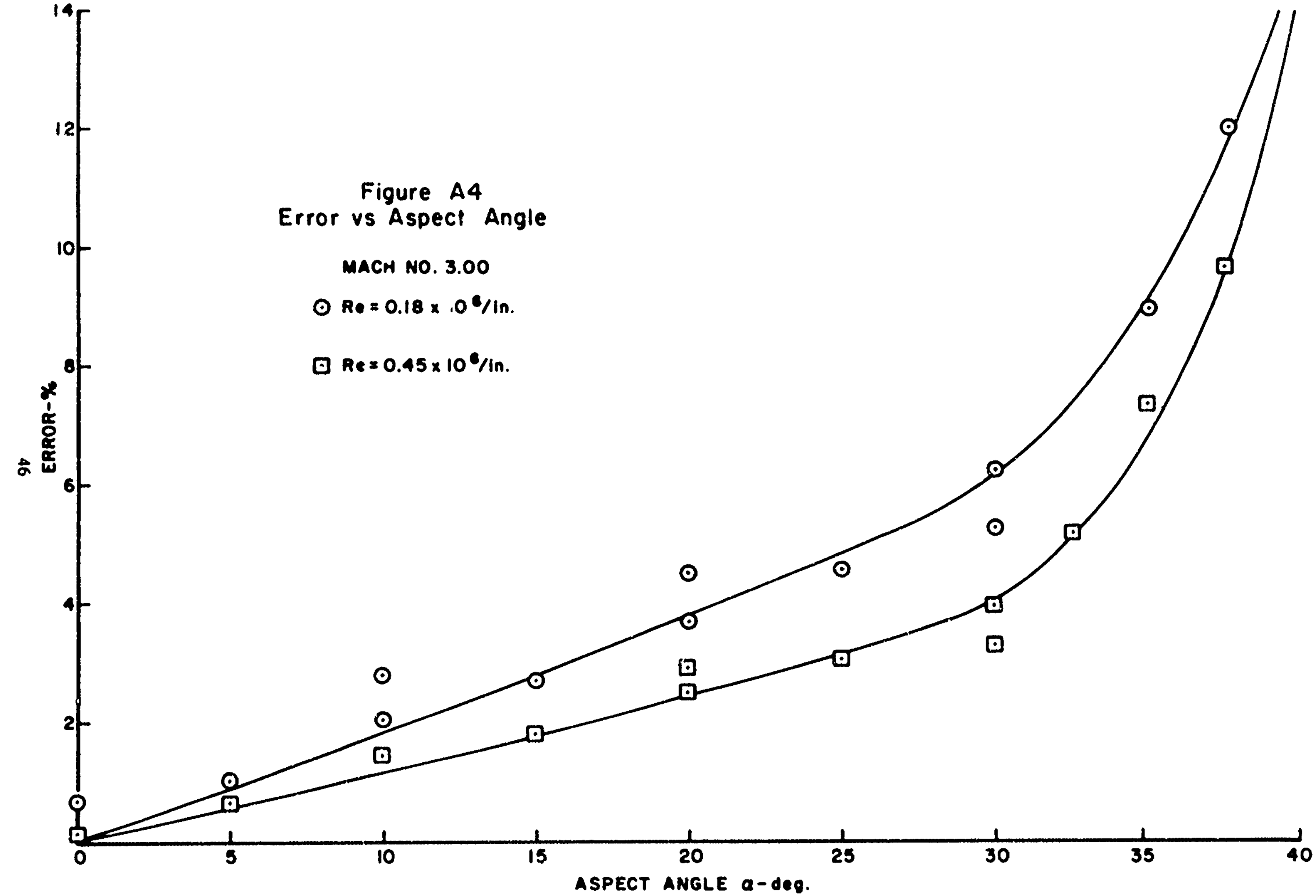


Figure A4
Error vs Aspect Angle

TABLE A-X

SSWT Test M = 3.50 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-60.38	-59.98	-11.270	3.739		
5	-60.46	-60.06	-11.285	3.724	0.015	0.40
10	-60.58	-60.18	-11.308	3.701	0.038	1.02
15	-60.91	-60.51	-11.370	3.639	0.100	2.67
20	-61.20	-60.80	-11.424	3.585	0.154	4.12
25	-61.53	-61.13	-11.486	3.523	0.216	5.78
30	-61.82	-61.42	-11.541	3.468	0.271	7.25
35	-62.77	-62.37	-11.719	3.290	0.449	12.01
40	-64.63	-64.23	-12.069	2.940	0.799	21.37
37.5	-63.15	-62.75	-11.791	3.218	0.521	13.93
32.5	-62.04	-61.64	-11.582	3.427	0.312	8.34
30	-61.76	-61.36	-11.529	3.480	0.259	6.93
25	-61.51	-61.11	-11.482	3.527	0.212	5.67
20	-61.26	-60.86	-11.435	3.574	0.165	4.41
10	-60.78	-60.38	-11.345	3.664	0.075	2.01
0	-60.45	-60.05	-11.283	3.726	0.013	0.35

Patm = 15.009 psia

Static Gage Zero -0.40 mv

TABLE A-XI

SSWT Test M = 3.50 Re = 0.45 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-30.26	-29.86	-5.611	9.400		
5	-30.26	-29.86	-5.611	9.400	0.000	0.00
10	-30.37	-29.97	-5.631	9.380	0.020	0.21
15	-30.91	-30.51	-5.733	9.278	0.122	1.30
20	-31.39	-30.99	-5.823	9.188	0.212	2.26
25	-31.82	-31.42	-5.904	9.107	0.293	3.12
30	-32.28	-31.88	-5.990	9.021	0.379	4.03
35	-34.76	-34.36	-6.456	8.555	0.845	8.99
40	-39.57	-39.17	-7.360	7.651	1.749	18.61
37.5	-35.87	-35.47	-6.665	8.346	1.054	11.21
32.5	-33.10	-32.70	-6.144	8.867	0.533	5.67
30.0	-32.40	-32.00	-6.013	8.998	0.402	4.28
20	-31.61	-31.21	-5.864	9.147	0.253	2.69
10	-30.75	-30.35	-5.703	9.308	0.092	0.98
0	-30.28	-29.88	-5.614	9.397	0.003	0.03

Patm = 15.011 psia

Static Gage Zero - 0.40mv

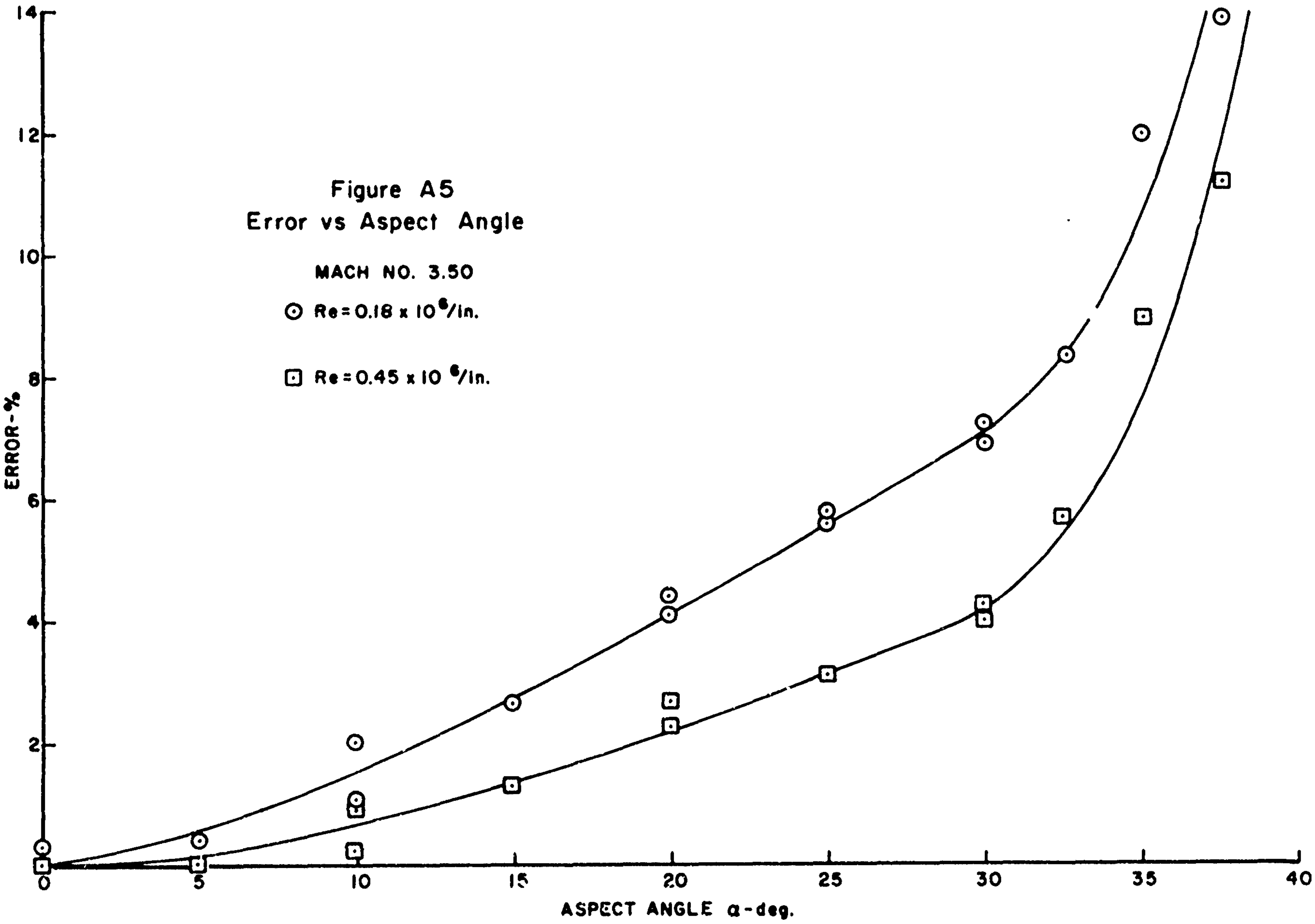


Figure A5
Error vs Aspect Angle
MACH NO. 3.50
Re=0.18 x 10^6/in.
Re=0.45 x 10^6/in.
ERROR-%
ASPECT ANGLE α-deg.
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
40

TABLE A-XII

SSWT Test M = 4.00 Re = 0.18 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-63.63	-63.47	-11.926	3.085		
5	-63.92	-63.74	-11.977	3.034	0.051	1.65
10	-64.07	-63.87	-12.001	3.010	0.075	2.43
15	-64.20	-63.98	-12.022	2.989	0.096	3.11
20	-64.47	-64.24	-12.071	2.940	0.145	4.70
25	-64.65	-64.40	-12.101	2.910	0.175	5.67
30	-64.87	-64.60	-12.138	2.873	0.212	6.87
35	-66.14	-65.85	-12.373	2.638	0.447	14.49
40	-67.88	-67.57	-12.696	2.315	0.770	24.96
37.5	-66.90	-66.58	-12.510	2.501	0.584	18.93
32.5	-65.40	-65.06	-12.225	2.786	0.299	9.69
30	-65.10	-64.74	-12.165	2.846	0.239	7.75
20	-64.77	-64.39	-12.099	2.912	0.173	5.61
10	-64.26	-63.86	-11.999	3.012	0.073	2.37
0	-63.94	-63.52	-11.935	3.076	0.009	0.29

Patm = 15.011 psia

Static Gage Zero -0.16 mv beginning
-0.42 mv end

TABLE A-XIII

SSWT Test M = 4.00 Re = 0.45 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-39.33	-38.91	-7.311	7.703		
5	-39.64	-39.22	-7.369	7.645	0.058	0.75
10	-39.87	-39.45	-7.413	7.601	.102	1.32
15	-40.00	-39.58	-7.437	7.577	.126	1.64
20	-40.57	-40.15	-7.544	7.470	.233	3.02
25	-40.94	-40.52	-7.614	7.400	.303	3.93
30	-41.25	-40.83	-7.682	7.332	.371	4.82
35	-44.03	-43.61	-8.194	6.820	.883	11.46
40	-48.19	-47.77	-8.976	6.038	1.665	21.61
37.5	-45.70	-45.28	-8.508	6.506	1.197	15.54
32.5	-42.14	-41.72	-7.839	7.173	.530	6.88
30	-41.31	-40.89	-7.683	7.331	.372	4.83
20	-40.76	-40.34	-7.580	7.434	.269	3.49
10	-39.95	-39.53	-7.428	7.586	.117	1.52
0	-39.37	-38.95	-7.315	7.699	.004	0.05

Patm = 15.014 psia

Static Gage Zero -0.42 mv

TABLE A-XIV

SSWT Test M = 4.00 Re = 0.62 x 10^6/in.

Aspect Angle	Gage Output Obs.	Gage Output Cor.	Total Head Pressure		Error	
Deg	mv	mv	psig	psia	psi	%
0	-22.75	-22.33	-4.196	10.817		
5	-23.20	-22.78	-4.280	10.733	.084	0.78
10	-23.55	-23.13	-4.346	10.667	.150	1.39
15	-23.77	-23.35	-4.387	10.626	.191	1.77
20	-24.45	-24.03	-4.515	10.498	.319	2.95
25	-24.88	-24.46	-4.596	10.417	.400	3.70
30	-25.19	-24.77	-4.654	10.359	.458	4.23
35	-29.16	-28.74	-5.399	9.614	1.203	11.12
40	-34.70	-34.28	-6.441	8.572	2.245	20.75
37.5	-31.70	-31.28	-5.878	9.135	1.682	15.55
32.5	-26.65	-26.23	-4.928	10.085	.732	6.77
30	-25.32	-24.90	-4.678	10.335	.482	4.46
20	-24.68	-24.26	-4.558	10.455	.362	3.35
10	-23.71	-23.29	-4.376	10.637	.180	1.66
0	-22.81	-22.39	-4.207	10.806	.011	0.10

Patm = 15.013 psia

Static Gage Zero -0.42 mv

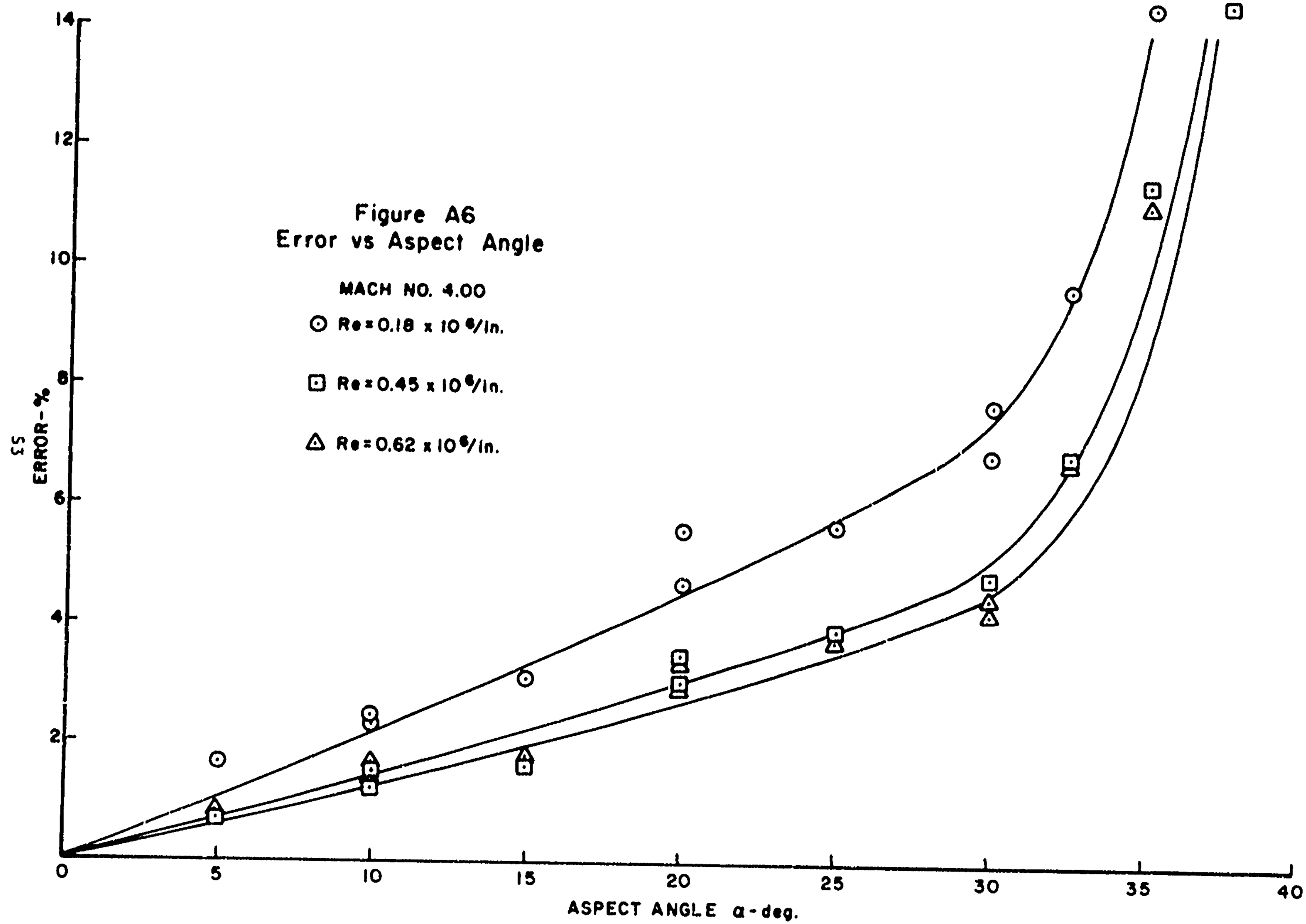


Figure A6
Error vs Aspect Angle

APPENDIX B

PROCEDURES AND TEST RESULTS FROM
EDGEWOOD ARSENALS TRANSONIC WIND TUNNEL TESTS

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APPENDIX B

Appendix B presents the data from the calibration test runs made in the Edgewood Arsenal's transonic wind tunnel. Figure B-1 shows the gage and mount. The unit was secured to a side wall mount of the tunnel on a rotating table which could be set at the desired angles of attack. At each Mach number, the millivolt output of the transducer was recorded from the digital volt meter in the instrumentation set-up.

The following explanation of the tables which follow holds true for all runs:

1. Column one, aspect angle (α) in degrees was read from the rotating table.
2. The second column observed gage output in millivolts, was visually read from a sensitive voltmeter after a reasonable steady state existed.
3. Column 3 is the barometric pressure recorded for each test point.
4. The fourth column, total head pressure in terms of absolute pressure, is the gage pressure determined from the gage output added to the atmospheric pressure.
5. Column 5, error in psi is obtained by subtracting the total head pressure at $\alpha = N^{o}$ from the pressure at $\alpha = o^{o}$.
6. The last column merely converts column 5 into percentage.

The runs were made at Reynolds numbers from 0.30×10^6/in. to 0.40×10^6/in.

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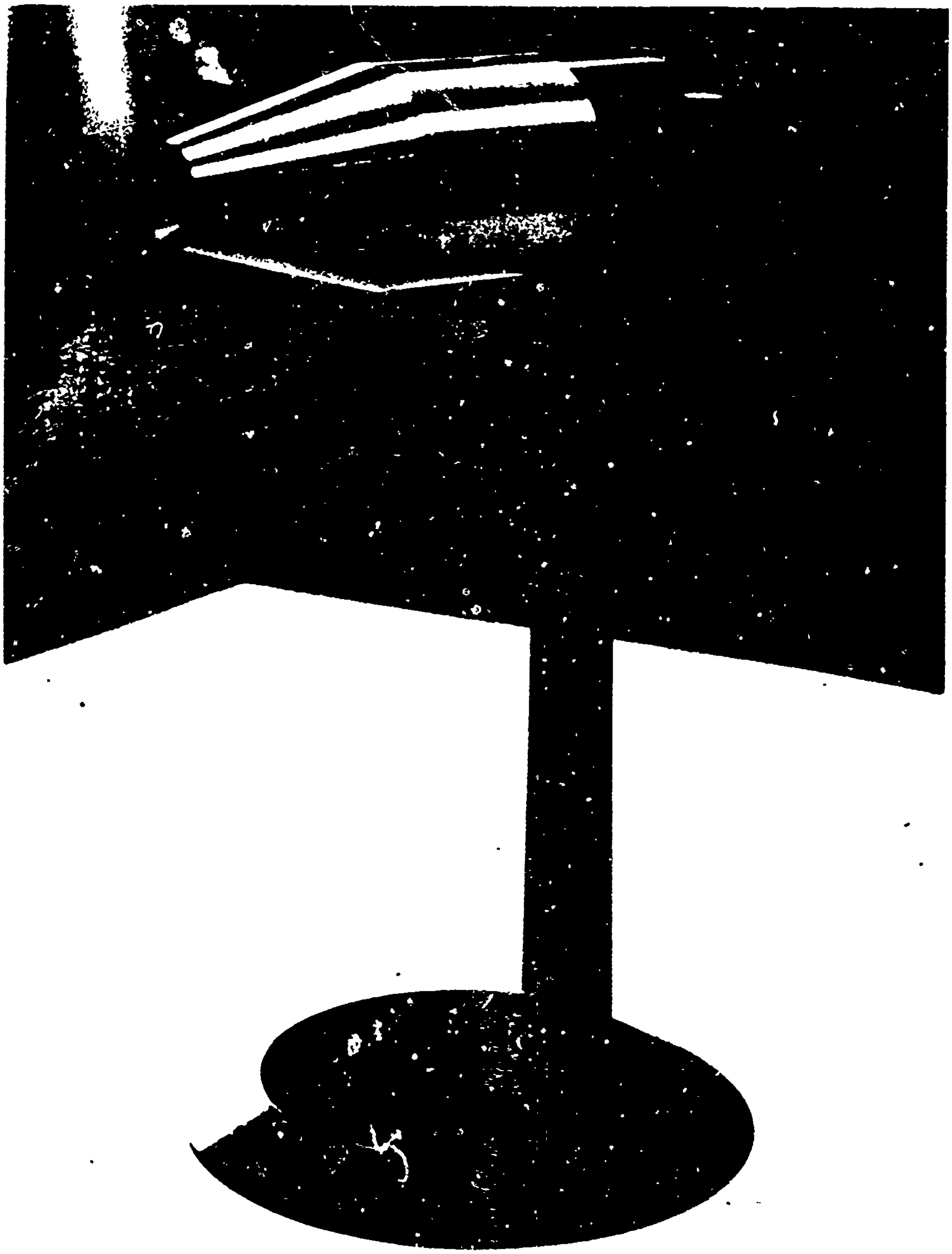

Figure B.1 Gage and Mount for TSWT Test.

TABLE B-I

TSWT Test M = 0.47 Re= 0.30×10^6/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	26.0	14.714	19.39	----	----
5	26.0	14.677	19.35	0.04	0.19
10	25.5	14.677	19.26	0.13	0.66
15	26.0	14.677	19.35	0.04	0.19
20	27.25	14.835	19.74	0.35	1.78*
22	26.0	14.866	19.54	0.15	0.78
28	26.0	14.717	19.40	0.01	0.02*
30	26.0	14.717	19.40	0.01	0.02*
32	25.5	14.717	19.30	0.09	0.45
34	25.25	14.717	19.26	0.13	0.68
36	24.5	14.717	19.12	0.27	1.45
38	23.75	14.717	18.99	0.40	2.73
40	22.5	14.717	18.77	0.62	3.23

*Data Points Questionable.

TABLE B-II

TSWT Test $M = 0.67$ $Re = 0.324 \times 10^6/in.$

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	26.75	14.704	19.51	----	----
5	26.5	14.704	19.47	0.04	0.21
10	26.0	14.704	19.38	0.13	0.67
15	27.0	14.704	19.56	0.05	0.25
20	26.5	14.704	19.47	0.04	0.21
22	26.5	14.696	19.46	0.05	0.25
24	26.5	14.673	19.44	0.07	0.36
26	26.0	14.673	19.35	0.16	0.82
28	25.0	14.673	19.17	0.34	1.74
30	25.0	14.603	19.10	0.41	2.10
32	24.5	14.603	19.01	0.50	2.56
34	23.25	14.603	18.78	0.73	3.74
36	23.5	14.603	18.83	0.68	3.49
38	21.0	14.603	18.38	1.13	5.79
40	17.5	14.603	17.75	1.76	9.02

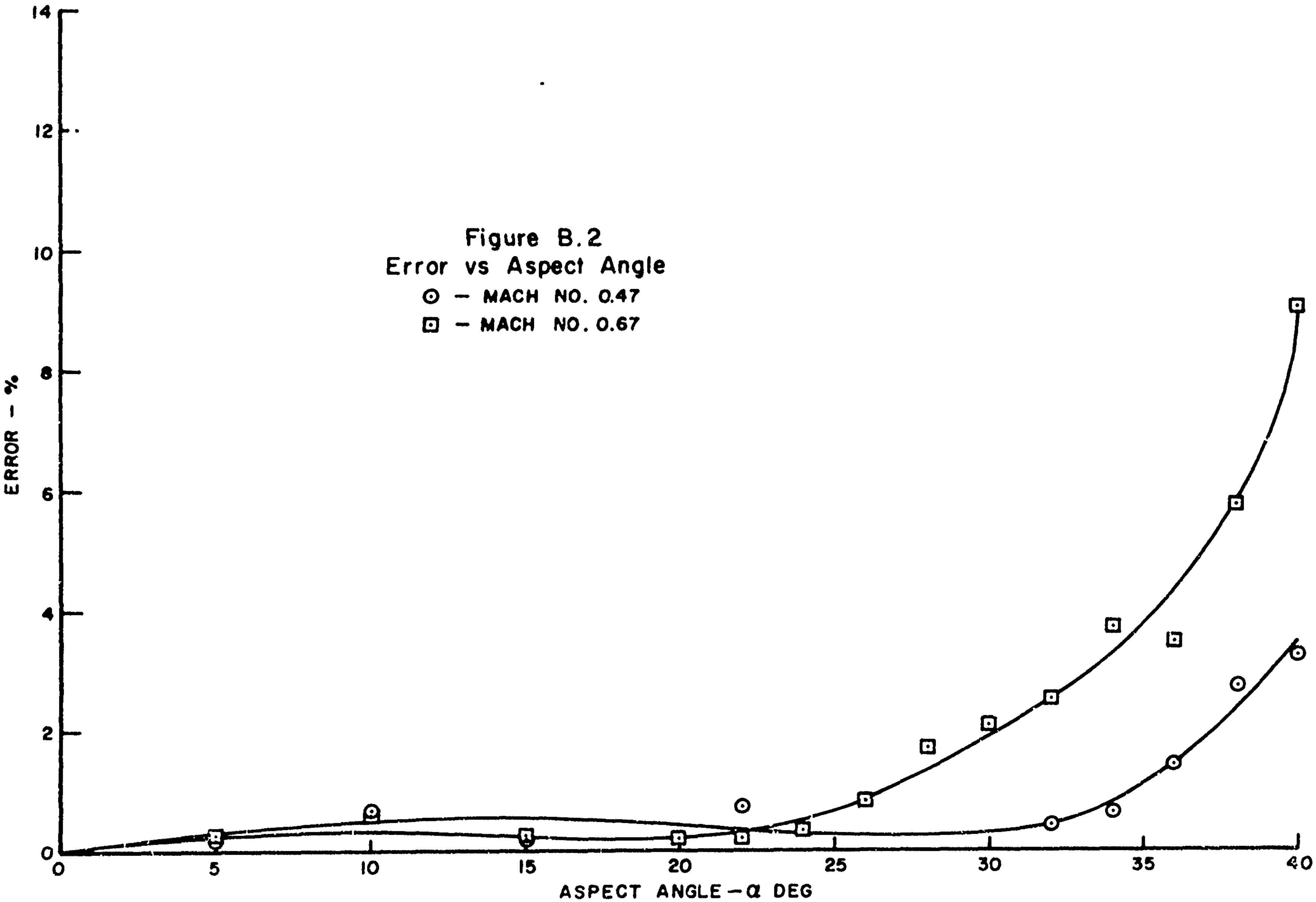

Figure B.2
Error vs Aspect Angle

TABLE B-III

TSWT Test M = 0.90 Re= 0.375×10^6/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	53.0	14.615	24.15	----	----
5	54.5	14.715	24.51	0.36	1.49
10	53.0	14.715	24.25	0.10	0.41
15	52.0	14.715	24.06	0.09	0.37
20	52.5	14.715	24.15	0	0
22	52.0	14.715	24.06	0.09	0.37
24	52.0	14.715	24.06	0.09	0.37
26	51.25	14.717	23.93	0.22	0.91
28	51.0	14.743	23.91	0.24	0.99
30	51.0	14.743	23.91	0.24	0.99
32	50.5	14.723	23.80	0.35	1.45
34	49.75	14.717	23.66	0.49	2.03
36	47.0	14.708	23.16	0.99	4.10
38	43.75	14.698	22.56	1.59	6.58
40	40.5	14.696	21.98	2.17	8.98

TABLE B-IV

TSWT Test M = 0.95 Re= 0.362 x 10^6/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	54.0	14.565	24.27	----	----
5	52.75	14.561	24.05	0.22	0.91
10	53.0	14.528	24.06	0.21	0.84
15	53.0	14.497	24.03	0.24	0.99
20	52.5	14.505	23.95	0.32	1.32
22	52.0	14.505	23.86	0.41	1.69
24	51.5	14.547	23.81	0.46	1.90
26	52.5	14.545	23.99	0.28	1.15
28	52.25	14.545	23.94	0.33	1.36
30	51.5	14.545	23.81	0.46	1.89
32	51.0	14.545	23.72	0.55	2.27
34	49.5	14.541	23.44	0.83	3.42
36	47.0	14.543	22.99	1.28	5.27
38	44.5	14.545	22.55	1.72	7.10
40	39.0	14.545	21.56	2.71	11.16

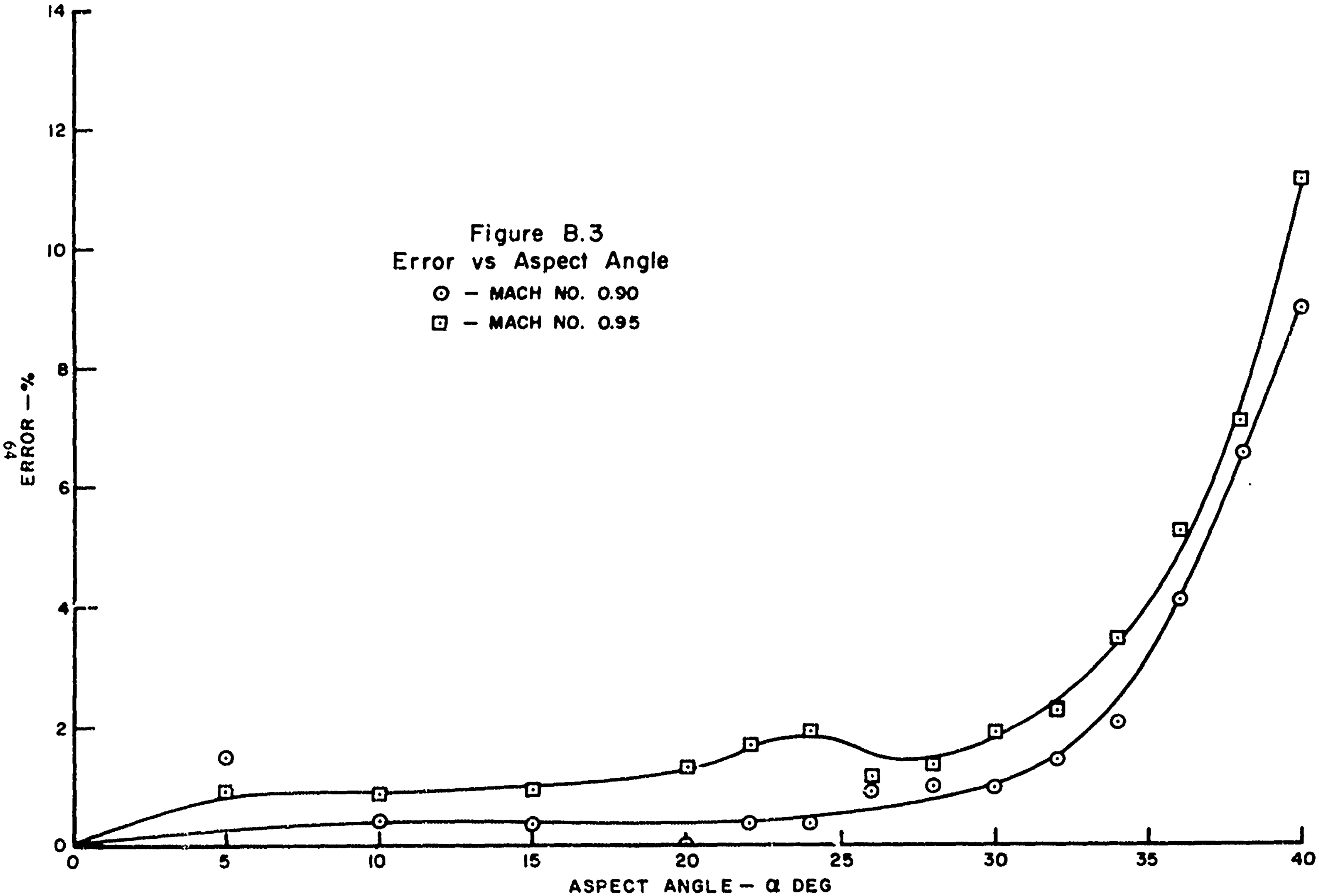

Figure B.3
Error vs Aspect Angle

TABLE B-V

TSWT Test M = 1.00 Re= 0.35 x 10^6/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	56.0	14.735	24.81	----	----
5	55.0	14.696	24.59	0.22	0.89
10	54.5	14.700	24.50	0.31	1.25
15	53.5	14.698	24.32	0.49	1.97
20	53.25	14.692	24.27	0.54	2.18
22	53.0	14.690	24.22	0.59	2.38
24	52.5	14.677	24.12	0.69	2 78
26	52.5	14.677	24.12	0.69	2.78
28	51.0	14.679	23.85	0.96	3.87
30	52.25	14.630	24.03	0.78	3.14
32	51.5	14 634	23.89	0.92	3.71
34	50.0	14.627	23.62	1.19	4.80
36	47.25	14.619	23.12	1.69	6.81
38	43.5	14.605	22.43	2.38	9.59
40	40.25	14.584	21.82	2.99	12.05

TABLE B-VI

TSWT Test M = 1.05 Re= 0.33×10^6/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	psi	psia	psi	%
0	53.5	14.568	24.19	----	----
5	54.25	14.565	24.32	0.13	0.54
10	53.5	14.561	24.18	0.01	0.04
15	53.75	14.638	24.30	0.11	0.45
20	52.25	14.640	24.04	0.15	0.62
22	52.50	14.642	24.08	0.11	0.45
24	51.50	14.650	23.91	0.28	1.16
26	52.0	14.657	24.01	0.18	0.74
28	52.0	14.673	24.02	0.17	0.70
30	51.25	14.677	23.89	0.30	1.24*
32	51.0	14.677	23.85	0.34	1.40
34	50.5	14.677	23.76	0.43	1.77
36	46.0	14.770	23.04	1.15	4.75*
38	42.5	14.770	22.41	1.78	7.36
40	38.5	14.772	21.70	2.49	10.29*

*Data questionable, Not used in plotting.

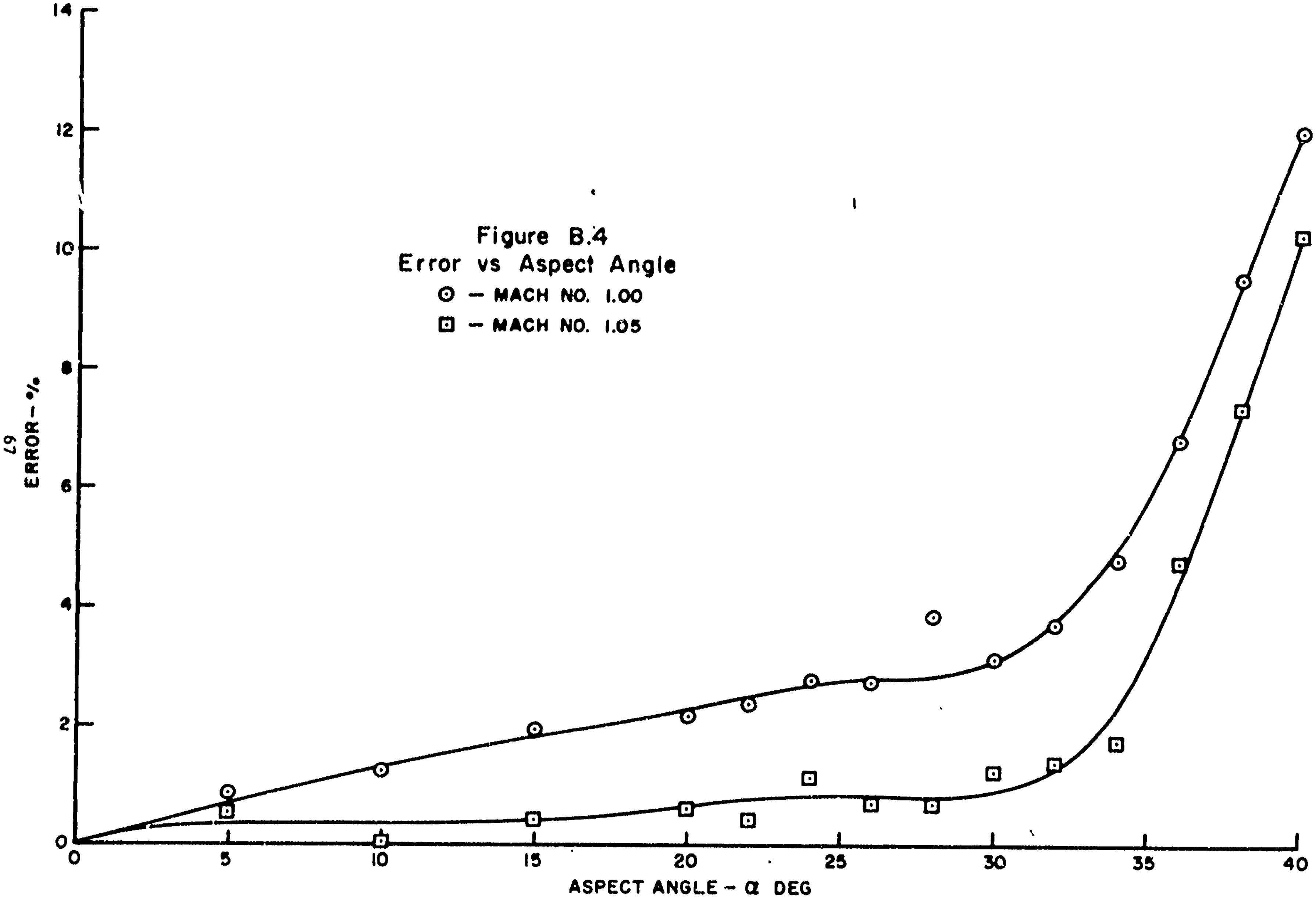
Figure B.4
Error vs Aspect Angle
⊙ — MACH NO. 1.00
⊡ — MACH NO. 1.05
ERROR — %
ASPECT ANGLE — α DEG
0
2
4
6
8
10
12
14
5
15
20
25
30
35
40

TABLE B-VII

TSWT Test $M = 1.09$ $Re = 0.377 \times 10^6$/in.

Aspect Angle	Gage Output	Patm	Total Head Pressure	Error	
Deg.	Mv.	Psi	psia	psi	%
0	76.5	14.721	28.48	----	----
20	76.25	14.719	28.43	0.05	0.17
30	73.0	14.717	27.84	0.64	2.25
36	67.5	14.580	26.72	1.76	6.18
38	64.5	14.580	26.18	2.30	8.07
40	60.5	14.565	25.44	3.04	10.67

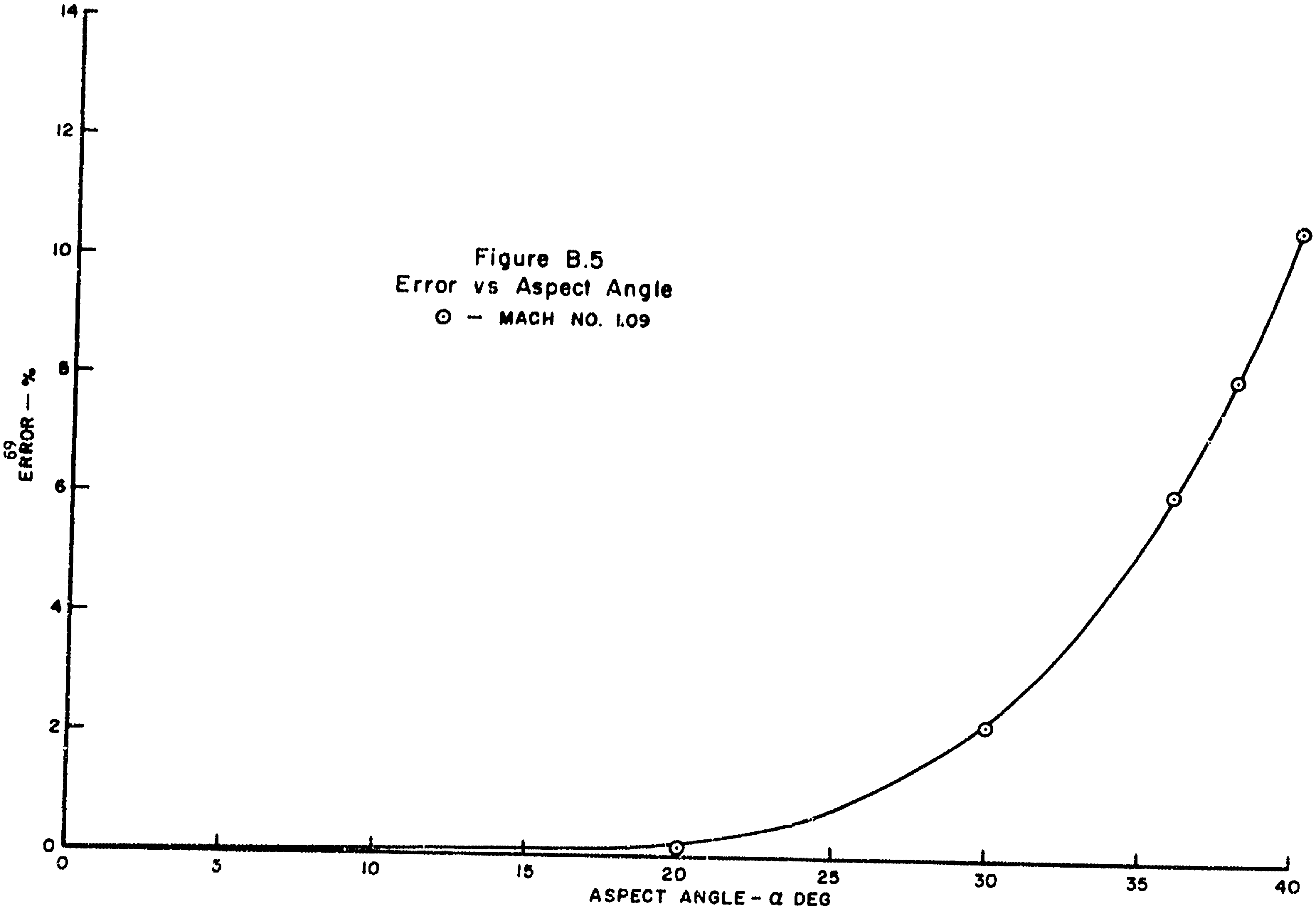

Figure B.5
Error vs Aspect Angle